

## APPLICATION OF A DISTRICT HEATING NETWORK (DHN) MODEL FOR AN EX-ANTE EVALUATION TO SUPPORT A MULTI-SOURCES DH

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### ABSTRACT

With growing environmental concern, increasing urban population and energy needs, district heating networks are considered as a promising sustainable energy solution. They enable to combine several energy sources in order to bring cost-effective and environmentally friendly solutions. This paper presents a new flexible tool which can model various network architectures, using an oriented graph structure to represent a DH network. At each time step, network running is simulated via linear programming formalism. The purpose of this tool is not the optimization of the network, but the emulation of its functioning. It can be used at different stages of the DHN life. The study focuses on an application of this DH model, which could help decision makers during the design process of a multi-sources DH network, through evaluations and comparisons of economic and energy aspects of the system under different scenarios.

### INTRODUCTION

A significant proportion of the European heating needs (10%) is supplied by DH networks (CETE Ouest, 2012) : DH contribution is very different from one country to another according to the local policies (e.g. in 2007, 95% in Island, 30% Romania, 5% in France) (CETE Ouest, 2012). Compared to other heating solutions, DH networks have the main advantages to improve energy efficiency (e.g. through heat and power cogeneration) and to facilitate the use of renewable and local energy resources such as biomass, waste heat or geothermal energy. In countries where heating is necessary, DH is viewed as a promising sustainable energy solution which could enable reduction targets of greenhouse gases emissions to be met, at a reasonable cost. However DH networks require important investment costs and initial design engages a combination of many different parameters in a complex process. So, making DH networks an effective leverage for local energy policy and urban planning requires tools for decision making.

DH network models which are reviewed in the literature are generally specialized optimization models. They can be classified into two main categories according to their particular objectives.

Firstly support decision tools aim at evaluating scenarios at the design stage. They can target network topology optimization (Söderman et al., 2006), network design optimization (Gustafsson et al., 1991), or energy-mix optimization (Lundand et al., 2010). The second category gathers real time management tools, mid-term and long-term tools, in order to optimize the DH network operating (Zhao et al., 1998, Dotzauer, 2003) with different time horizons.

Different levels of details may be adopted for elementary model equations and for input parameters, depending on model objectives. For instance the PipeLab model (Yildirim et al., 2010), which aims at optimizing the design of pipes of a geothermal DH network, takes into account technical pipes' variables (pressure losses, material, etc.), whereas the Persson's model (Persson et al., 2011) dealing with DH competitiveness rather considers economical and cost parameters. Verda (Verda et al., 2011) mainly uses thermo-hydraulic parameters and fluid dynamic parameters to propose an optimization model for operating and control of a multi-scale storage.

In general existing optimization models use linear programming (Söderman et al., 2006), mixed integer programming algorithms (Gustafsson et al., 1991), and more occasionally non-linear programming algorithms (Brun, 2010). The choice of an optimization algorithm depends on the type of unknown variables and on the complexity of the equations used. Linear programming is often used because of its ability to represent networks and its efficiency to find a global solution to the optimization problem. In all DH models, optimization routines always minimize a cost function. This objective function can either be the total cost of the DH network (investment costs and operating costs) (Persson et al., 2011) or only the cost of the energy supplied to customers (Aberg, Henning, 2011). When the DH network incorporates a CHP unit, electricity purchase can also be considered (Tveit et al., 2009): profit from the electricity sale is deducted from the total costs.

Regarding heat production systems, some models consider several production systems (heat pumps, combined heat and power (CHP), boilers, etc.)

(Aberg, Henning, 2011), while others account only for a CHP unit (Genon et al., 2009). It can be noted that a CHP unit is present in all the models analyzed. The total simulation period is in general split into time steps when fuel's price or demand intensity is changing over time (Dotzauer, 2003). Time step varies from hours to one year depending on the aims of the model and the type of users considered.

Due to their very precise targets, existing models generally lack of flexibility, both concerning typologies of networks which can be modeled and regarding questions which can be answered.

This paper focuses on an energy model which simulates a DH network running on a given period (typically one year), based on heat load data (real data or simulated data resulting from another model of energy demand simulation). This DH model is designed to be coupled with an economical model and an environmental model, to form a global strategic management tool suitable for ex-ante and ex-post multi-criteria evaluation of DH networks.

After a description of the DH model's principles and structure, a case study is performed, with several scenarios of a real network being studied, to illustrate how this model can be used and what are the conclusions that come with it, to define a strategy of management.

## DESCRIPTION OF THE MODEL

The district heating is assumed to be fully described *a priori*, with its topology and set of pipes and substations. Customers are connected to substations and various known sources provide heat to the network.

### **Structure of the model**

In the model a DH network is represented by an oriented graph and its energy behavior is simulated at each time step, using the linear programming formalism (De Werra, 1990), to optimize short-term resources allocation in a completely defined system. The optimization solver is only used to emulate the network operating. The model does not use an optimization approach but a simulation approach. The model considers variable flow rate and fixed supply and return temperatures, but it can be extended for fixed flow rate and variable temperatures. The length of the pipes are taken into account through the losses calculations. The model allows simulating scenarios with parameters that vary hourly, such as the available power of domestic waste incineration plants or fuel prices.

In the proposed model, a graph with  $n$  nodes and  $m$  branches stands for a DH network of  $n$  substations or heating plants, and  $m$  pipes. Each node incorporates one heat source and one heat sink. Heat flow is directed through pipes from one node to another and the graph is oriented :  $\{Pr(i)\}$  is the set of inlet

branches of node  $i$  (predecessors) and  $\{Su(i)\}$  is the set of outlet branches of node  $i$  (successors).

The basic network topology is provided to the model via a *simple graph format* (sgf matrix) which describes how the nodes and branches are linked together. All the other matrices describing the network topology (successor matrix, predecessor matrix, connectivity matrix, etc.), which are essential for the implementation of the optimization problem, are calculated from this sgf matrix.

### **Notations and equations**

The following notations are used for the  $(n + m)$  unknown variables (state variables) at time  $t$  :

- $Pm_j$ , heat flow transferred in branch  $j$ , ( $j = 1; \dots; m$ )
- $PSrce_i^{(t)}$ , power production from heat source of node  $i$ , ( $i = 1; \dots; n$ )

At each time step  $t$ , a node  $i$  is characterized by the following input parameters:

- $P_{Srce_i}^{\max(t)}$  maximal power of the heat source,
- $C_i^{(t)}$  operating cost of heat sources (accounting for plant efficiencies); costs used here are variable costs in order to represent priorities between heat sources for short term decision making ; investment cost is not considered,
- $P_i^{dem(t)}$  heat demand from heat sink,

With intermediate variables used in Equations 1 and 2:

$$P_i^+(t) = \sum_{j \in \{Pr(i)\}} Pm_j^{(t)} \quad \text{entering heat flow} \quad (1)$$

$$P_i^-(t) = \sum_{j \in \{Su(i)\}} (Pm_j^{(t)} + L_j^{(t)}) \quad \text{leaving heat flow} \quad (2)$$

In the same way, at each time step  $t$ , a branch  $j$  has:

- a maximal handled heat power  $Pm_j^{\max(t)}$
- heat losses  $L_j^{(t)}$  assumed to be affine function of handled power

To calculate the values of the state variables, the model minimizes the heat production cost of the whole network at each time step, while accounting for constraints. There are three different types of constraints at each node: thermal pipes capacity constraints (Equation 3), heat sources capacity constraints (Equation 4) and energy balance constraints (Equation 5) :

$$0 \leq Pm_j^{(t)} \leq Pm_j^{\max(t)} \quad \text{for each branch } j \quad (3)$$

$$0 \leq P_{Srce_i}^{(t)} \leq P_{Srce_i}^{\max(t)} \quad \text{for each heat source } i \quad (4)$$

$$P_i^+(t) + P_{Srce_i}^{(t)} = P_i^-(t) + P_i^{dem(t)} \quad \text{for each consumer node } i \quad (5)$$

At each time step the objective function  $f$  to minimize with this set of constraints is the global

heating cost in the whole network such as Equation 6.

$$f^T X = C(1)X(1) + C(2)X(2) + \dots + C(m+n)X(m+n) \quad (6)$$

In this optimization problem, all the equations and the objective function are linear. The linear programming (LP) formalism is then obviously chosen for being the simplest way to tackle this kind of problems. Besides LP can handle a great number of variables, which is not necessarily the case for the non-linear formalism (Brun, 2010), and it allows finding a global minimum of the objective function and not only a local minimum (Jacquet-Lagrèze, 1998).

The optimization problem is solved by using a variant of Mehrotra's predictor-corrector algorithm (Zhang, 1995), a primal-dual interior-point method (Mehrotra, 1992). This algorithm can be considered as a Newton-like method that solves simultaneously the primal and the dual programs. The iterates are kept in the strictly interior region represented by the inequality constraints. The optimization problem is stated using an LP standard matrix format as follow:

The objective function is  $\min_x f^T X$  and the system of constraints is such as

$$\begin{cases} A \cdot X = b & (7) \\ lb \leq X \leq ub & (8) \end{cases}$$

The Equation 7 represents the linear equalities.  $\dim(A) = (n, m+n)$  matrix and  $\dim(b) = (1, n)$ . The Equation 8 fixes the boundaries of the variables, with  $lb$  and  $ub$  stand for *lower boundary* and *upper boundary*.

To simulate the DH network in operating conditions, the LP optimization solver is run at each time step to return the best combination of heating sources and power flows in pipes, that minimizes the operating cost with respect to constraints. The optimization routine emulates the economic dispatch. Any time period and time steps may be used. Time steps longer than one hour can be simulated, leading to faster results.

## CASE STUDY

The model proposed is applied to a French district heating network located on the east side of the city of Nantes, in the district of Malakoff-Beaulieu. This network is 22km long and has 116 substations, equivalent to 16 000 housings (CETE Ouest, 2006). It provides around 130 000 MWh of heat to various public services customers such as hospitals, swimming pools, the congress center, schools, the train station, a mall and many apartment buildings. A smaller number of private customers are also connected to the network. The heat is provided to the network under the form of hot water from one central distribution point through a tree structure with multiple branches. It is continuously supplied by a

waste incineration plant and oil and gas boilers provide auxiliary heat when necessary (42MW). The incineration plant uses municipal solid waste, biological waste from local hospitals and other industrial wastes. The two hospitals connected to the network have their own boilers of 6MW and 10MW to secure their heat needs. 69% of the network operates at a high temperature and pressure levels (175°C-110°C under 29 bars), while the other 31% has lower operating conditions (110°C-80°C under 3 bars).

The waste incineration plant is modeled as a heat production source for which each variable can vary temporarily and with a very low production cost. Its maximum heat power is computed at each time step, using the Equation 9:

$$P_{max}(t) = LHV(t) * r(t) * \eta(t) * d(t) \quad (9)$$

Where  $LHV$  is the Lower Heating Value of the waste (GJ/t),  $r$  is the waste fuel rate (t/h),  $\eta$  is the incinerator efficiency and  $d$  is the availability of the incinerator. In this example,  $\eta = 0.75$  and the others parameters are varying over time (Figure 1 and 2).

Energy planning issues of this district heating network, are mainly focused on long-term decisions such as network expansion with or without additional heat production capacity or introducing new energy sources and technologies. The actual system schematic is simplified with the original 116 substations being aggregated in 23 nodes of an oriented tree as it is illustrated by Figure 3.

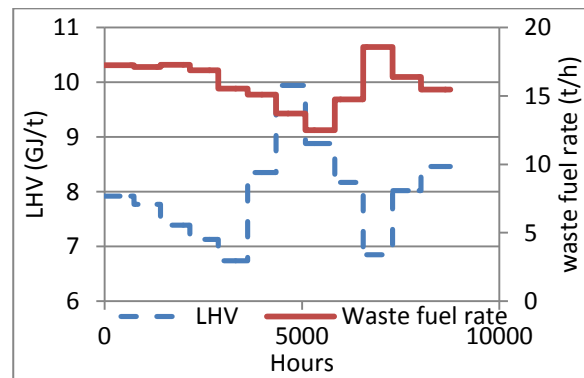


Figure 1: Lower Heating Value and waste fuel rate of the waste incinerated

The simulations use data from the network operator. The heat demand for a year is around 119 GWh while the total heat supplied to the network is 131 GWh. Input data for heat demand are monthly heat consumption for every substation. Six different types of consumers are identified (schools, hospitals, residential, administration, sport facilities, public places) with a specific share between space heating, water heating and process heat. A specific hourly time profile is defined for each use.

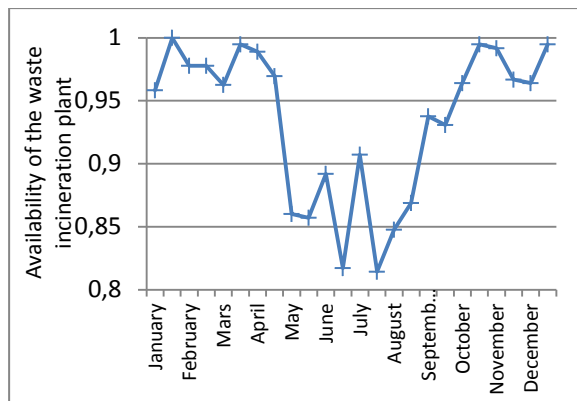


Figure 2: Fortnightly average of the availability of the waste incineration plant

The maximum powers supported by the pipes are between 1.8MW to 61MW, according to the zone considered. Costs are other important parameters that influence the choice of the heat production source. The model takes into account only the marginal costs which determine the merit order of each energy plant at each time step. For the Malakoff case study, marginal production cost from the waste incineration plant (0.001€/MWh) is much more lower than the cost from the thermal plant (0.04€/MWh) mainly related to fuel cost.

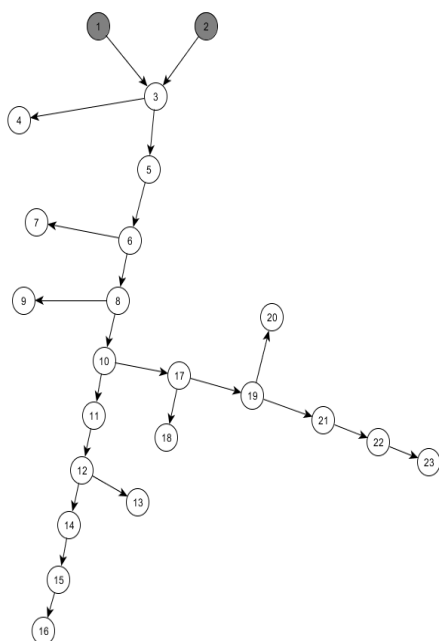


Figure 3: Diagram of the network of Malakoff. In grey the two main heat production sources

### Description of the scenarios

Three scenarios are implemented and analyzed:

*Scenario 1 (reference case)* : the main heat production source is a waste incineration plant and the extra heat is supplied by a thermal plant using a fossil fuel boiler.

*Scenario 2* : A storage is added to the same configuration as the scenario 1. The storage capacity is 400MWh.

*Scenario 3* : the main heat production source is a waste incineration plant with a reduced capacity compared to scenario 1 (-50%), the extra heat is supplied by a thermal plant (22MW) and thermal solar panels (20 000m<sup>2</sup>) are added.

### Results

The power delivered by the waste incineration plant and the thermal plant during the 3500 first hours of the year are represented in Figure 4.

In Figures 5 and Figure 6 a seven-days moving average is used in order to smooth the original fluctuations. They illustrate the heat load curve (demand power sorted in descending order), and the respective contribution of the other heat sources over a year for the scenario 1 and 3 respectively. Excess heat from the waste incineration plant and thermal solar panels are also represented. Since the graphs of the scenarios 1 and 2 are very similar, the figure corresponding to the scenario 2 is not presented.

In the scenario 1 (reference case), the waste incineration plant covers the major part of the yearly heating needs (91%). This heat source is sufficient for a needed power up to 28MW. When the power demand is higher, the fossil fuel boiler is needed. It supplies 8.9% of the extra heat demand. The waste incineration plant produces between 1MW and 26MW of excess heat during around 1500 hours of the year. Although a significant excess energy from the waste incinerator can be observed, compared to the yearly heating load, the corresponding heat is insufficient during peak hours.

The results of the scenario 2 are very similar to the reference case. In the scenario 2 the waste incineration plant is the energy base source production, it satisfies the most important part of the heating needs (91%). The extra heat demand is supplied by the fossil fuel thermal plant (8.4%). The storage accounts only for 0.6% of the heat demand, despite of its significant capacity.

The scenario 3 proposes a very different energy balance. The main production source is still the waste incineration plant which account for 60.3% of the heat production, while the thermal plant and the solar panels supply respectively 35.6% and 4.1% of the demand. Solar panels have a limited contribution partly due to the high temperature of the network. The waste incineration plant can satisfy a demand up to 13MW. When the demand becomes higher the thermal solar panels contribute to 1MW before the fossil fuel boiler is used to satisfy all demand. In the scenario 3, the waste incineration plant has a reduced capacity of production (-50%), it produces between 1MW and 11MW of excess heat during 4500 hours and there is between 1MW and 5MW of excess heat coming from the thermal solar panels.

Table 1:  
Energy balance for the three scenarios analyzed

	Distributed energy (MWh)	Heat source	Covering ratio	Total losses (MWh)
<b>Scenario 1 (reference case)</b>	121 581	Waste incineration plant	91.1%	15 272
	11 906	Thermal plant	8.9%	
<b>Scenario 2</b>	121 818	Waste incineration plant	91.0%	15 627
	11 320	Thermal plant	8.4%	
	868	Storage	0.6%	
<b>Scenario 3</b>	79 107	Waste incineration plant	60.3%	13 052
	46 801	Thermal plant	35.6%	
	5 359	Solar panels	4.1%	

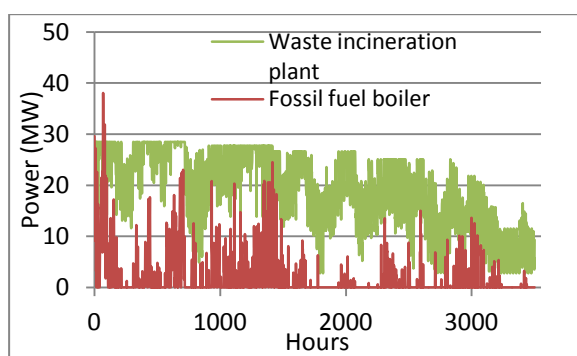


Figure 4: Power delivered by the waste incineration plant and the thermal plant for the beginning of the year

Table 2 presents the cost analysis resulting from the heat production dispatching for each scenario. In the scenario 2 the introduction of heat storage leads to an average cost, (of 4.30€/MWh), lower than in the scenario 1 (4.48€/MWh). Meanwhile in the scenario 3 the total production cost and so the average cost of a MWh (respectively 1 957k€ and 14.90€/MWh) is much more important than in the scenario 1 (598k€ and 4.48€/MWh) due to the higher proportion of the fossil fuel thermal plant (36%).

Table 2  
Cost analysis for the three scenarios

	Average cost (€/MWh)	Total cost (k€)
<b>Scenario 1 (reference case)</b>	4.48	598
<b>Scenario 2</b>	4.30	576
<b>Scenario 3</b>	14.90	1 957

This example illustrates how important it is to compare different possibilities in order to choose the best scenario. Here the model underlines the significant excess heat (visible on the dotted area of the graphs) produced by the waste incineration plant.

## DISCUSSION AND PERSPECTIVES

### Using the model : examples

The model proposed here is a support decision tool. At the design stage, it is very important to evaluate different scenarios of DH networks (concerning different energy mixes or network topologies) in order to select the best adapted one, given that a DH network constitutes a long-term investment (*ex-ante* use of a model). In the same way, the assessment of a DH network, at operating stage (*ex-post* use) is essential in order to check and improve its energy, environmental and economical performances. This tool enables to model a large range of scenarios which vary in terms of demand structure, network architectures and energy technologies. It is particularly adapted for the modeling of big sized multi-sources networks (especially when there are several waste heat sources), and smaller networks in a complex situation with time-varying parameters, such as prices or available power.

The objective is not the optimization of a set of parameters, but an evaluation of the energy performances of a given DH network, through the long term simulation of its functioning (Ouarghi et al., 2007).

### Strengths of the model

The model presented in this paper is a general simulation tool. It has been developed in order to simulate a large panel of scenarios.

The model is suitable for any network topology, temporary problems can be modeled by modifying the maximal heat flow transported through pipes.

The model can tackle very different demand profiles, interconnections with other DH networks and associate “virtual sources” to consumer nodes. It means that some customers can temporarily use a personal heat source as an independent heat producer, for its own supply, at a specific partial disconnection cost.

A large range of heat production plants can be considered, provided that their maximal capacity, efficiency and energy cost are known at each time step. Time varying features of energy sources (costs, available power) are tackled through input parameters. Heat sources with power or efficiency depending on network temperature (heat pumps, geothermy, solar, e.g.) can be also represented : their characteristics must be evaluated at each time step from network temperatures, before calling the linear programming routine. The model always gives the priority to the cheapest energy source.

Regarding the production costs, the model may consider specific costs, such as pumping costs or environmental taxes by giving a cost to heat transferred into branches where pumps are located, or by giving an additional cost to the concerned heat sources. The costs considered here are operating variable costs only; investments and fixed costs should be accounted for in a complete economical analysis. Using CO<sub>2</sub> and other pollutants emission factors from fossil fuels and waste incineration would enable environmental impacts to be assessed, prior to complete LCA if required.

#### **Limits of the model**

Linear Programming is the simplest formalism for optimization, based on linearity assumptions both for the cost function and for the constraints, with respect to state variables. It has been chosen to emulate the DHN operating, because of its ability to find a global solution if there is a solution. However a drawback of using Linear Programming is that there could be an infinity of solutions when the problem is degenerated, meaning that there can exist specific situations (e.g. heat sources with the same operating costs) where the model cannot return one solution. Input data must be checked to avoid such situations.

Heat sources with non-constant efficiencies cannot be tackled directly with the linear model, they would require non-linear optimization, which could complexify the problem and increase dramatically computation time (optimization routine is called once at each time step). Nevertheless, in most cases, a simplified solution could be performed using mixed - integer linear programming based on linear interpolation of the cost function by intervals. Computation time should remain acceptable but this solution is still to be tested.

To provide valuable information, the model requires a certain amount of input data at a time step as precise as possible. This need of accurate and specific data constitutes a notable difficulty before being able to run the model. From the point of view of concerned stakeholders (local governments or operators), it is a strategic choice to collect and update the corresponding database in the long-run.

#### **CONCLUSION**

The model presented in this work is the core model of a more general management tool. Its particularity is due to its flexibility of modeling and to the way in which its energy results can be used through environmental and economic analyses. Some examples are given to illustrate how the model can be adapted to simulate various heat demand, network architectures, energy sources and conversion technologies.

This tool can be used as a basis of discussion between concerned stakeholders (network operator, customers, local authority, etc.) at different stages of the DH network life cycle. It can be a companion tool for decision making regarding different questions. Initial design or extension of a network can be tackled with the choice of a cost-effective and environmentally-friendly energy mix, and evaluation of the potential for future customers. Assessing actual performances of the network and comparing them to the forecasting is another application of such a tool (analyzing operating costs or checking whether carbon emission respect city's commitments).

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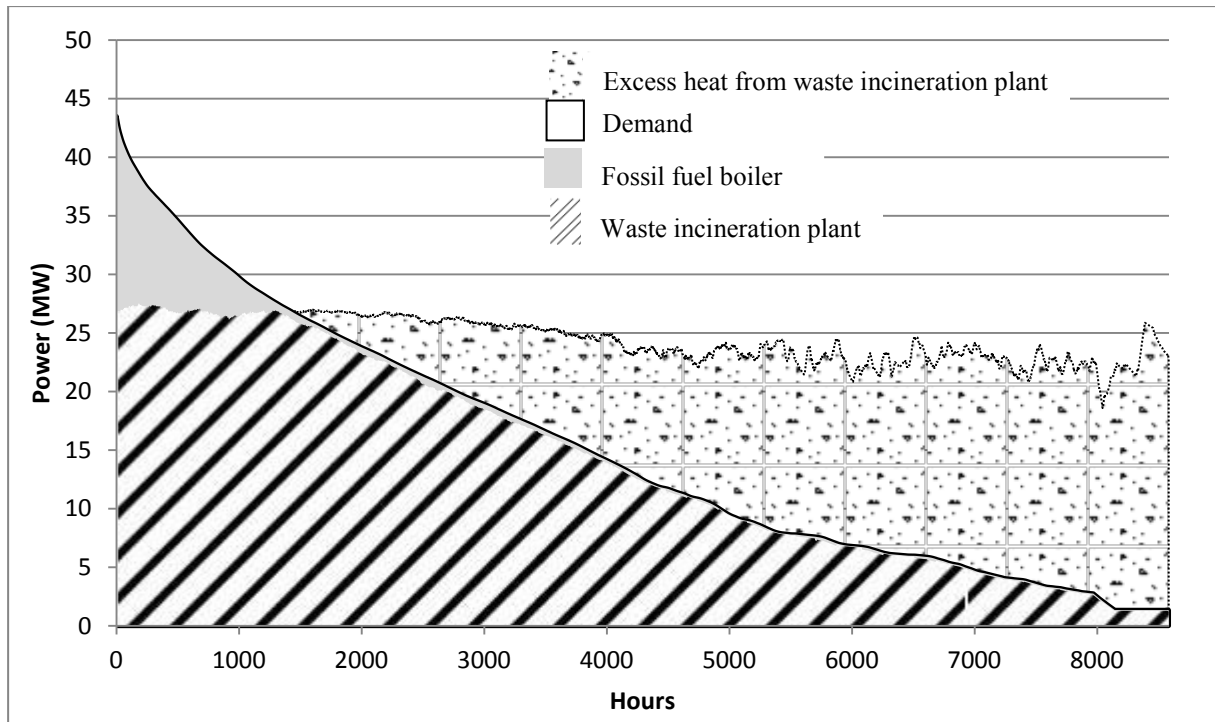


Figure 5: Hourly heat load curve (black line) and contributions provided by the waste incineration plant and fossil fuel thermal plant each hour of the year. Reference case (scenario 1)

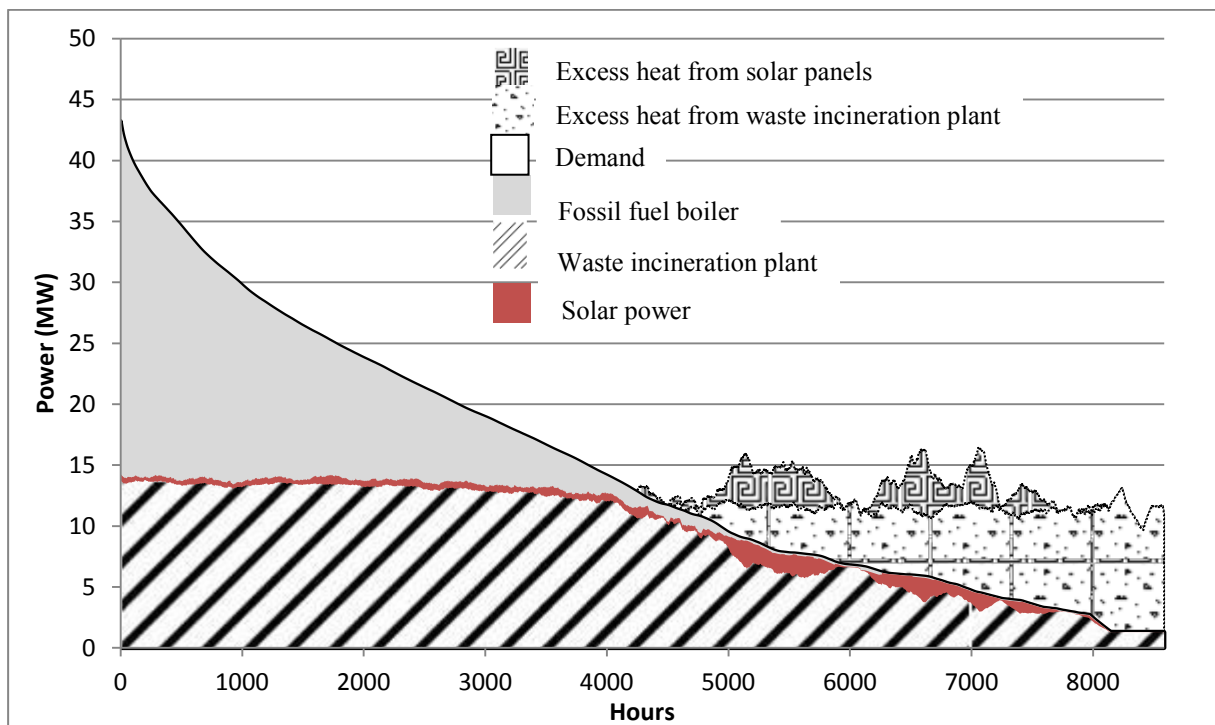


Figure 6: Hourly heat load curve (black line) and contributions from waste incineration plant, thermal solar collectors and fossil fuel thermal plant. Scenario 3